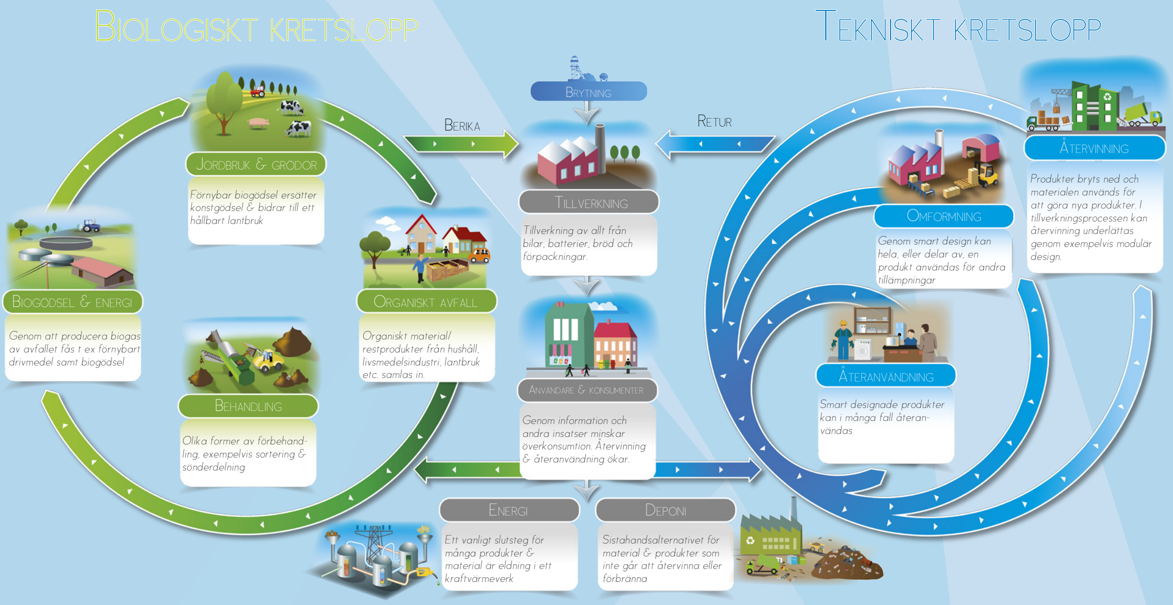
THE ROLE OF BIOGAS SOLUTIONS IN THE

CIRCULAR AND BIO-BASED ECONOMY



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The role of biogas solutions in the circular and bio-based economy

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Table of Contents

Preface

This report is written for Biogas Öst in the EU- project ”Prestudy for regional development of biogas infrastructure” by researchers at Linköping University, Biogas Research Center and the department of Environmental Technology and Management.

The project has been financed by European Regional Development Fund as well as by the region of Östergötland, County administrative Board of Västmanland, Uppsala regional council, the region of Örebro län, Sörmland regional council, County administrative Board of Uppsala, Biogas Öst, E.ON, AGA, Municipal company Vafab Miljö, Nordic Gas Solutions, Swedish Institute of Agricultural and Environmental Engineering– JTI, Linköpings Universitet (Biogas Research Center) and Heby municipality.

Förord

Denna rapport är framtagen åt Biogas Öst i EU-projektet ”Förstudie för regional utveckling av infrastruktur för biogas” av forskare vid Linköpings Universitet, Biogas Research Center och avdelningen för industriell miljöteknik.

Projektet har finansierats av Europeiska Regionala Utvecklingsfonden samt av Region Östergötland, Länsstyrelsen Västmanland, Regionförbundet Uppsala, Region Örebro län, Regionförbundet Sörmland, Länsstyrelsen Uppsala, Biogas Öst, E.ON, AGA, Kommunalförbundet Vafab Miljö, Nordic Gas Solutions, Institutet för miljö och Jordbruksteknik – JTI, Linköpings Universitet (Biogas Research Center) och Heby kommun.

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1. Introduction

Societal development faces many challenges. In the Swedish context, the competitiveness of industry and agriculture, sustainable city development and the transition to a more circular and bio-based economy are among the challenges informing this report. Such challenges may differ in other national contexts. But biogas solutions are generally versatile, flexible and cost efficient from a societal perspective, and when adapted to local conditions, may contribute to sustainable development.

The range and significance of biogas technologies has increased rapidly during the last 30 years. Solutions include for example wastewater treatment plants that use biogas processes for water cleaning and gas extraction; methane capture from old landfills; and anaerobic digestion from waste or energy crops. In the anaerobic process microorganisms decompose organic material during the formation of methane. Digestate is also formed and contains most of the nutrients from the organic materials entering the digestion process. This digestate can be used as fertiliser as long as it fulfils environmental criteria. Both biogas and digestate have a number of indirect effects on their surroundings worth of further study. They are renewable and bio-based, can replace fossil fuels and mineral fertilisers and contribute to regional development (Börjesson and Berglund, 2006; Energigas Sverige et al., 2015; WSP, 2011). These are examples of arguments found in literature about biogas. However, it is not always clear to what extent such arguments are supported by scientific studies.

Indirect effects of biogas solutions can contribute to development in line with the policy-driven concepts of "bio-based economy" and "circular economy" that are supposed to support societal change towards a more sustainable future. Bio-based economies can be defined as:

> "technological development that lead to a significant replacement of fossil fuels by biomass in the production of pharmaceuticals, chemicals, materials, transportation fuels, electricity and heat". (Langeveld et al., 2012)

A related concept is the bio-economy which is more related to the improving valorisation of biomass in the primary production sectors of agriculture and forestry.

Circular economy is defined by the Ellen McArthur foundation (2015) as

"A circular economy is restorative and regenerative by design, and aims to keep products, components, and materials at their highest utility and value at all times. The concept distinguishes between technical and biological cycles."

The concept of circular economy thus implies circular flows taking into account aspects like the value and quality of what is being circulated. It is illustrated in two different parts, one referring to the use of biomass and the other extracted materials. It is also relevant to consider the balance between the biological and the technical parts of the cycle. This is why the concepts of bio-economy or bio-based economy are useful. They both imply that the biological part of the cycle should increase its share in the total economy. This can be accomplished through substitution of fossil or mineral materials with biological ones, or through the growth of the bio-based share of the economy (Figure 1)

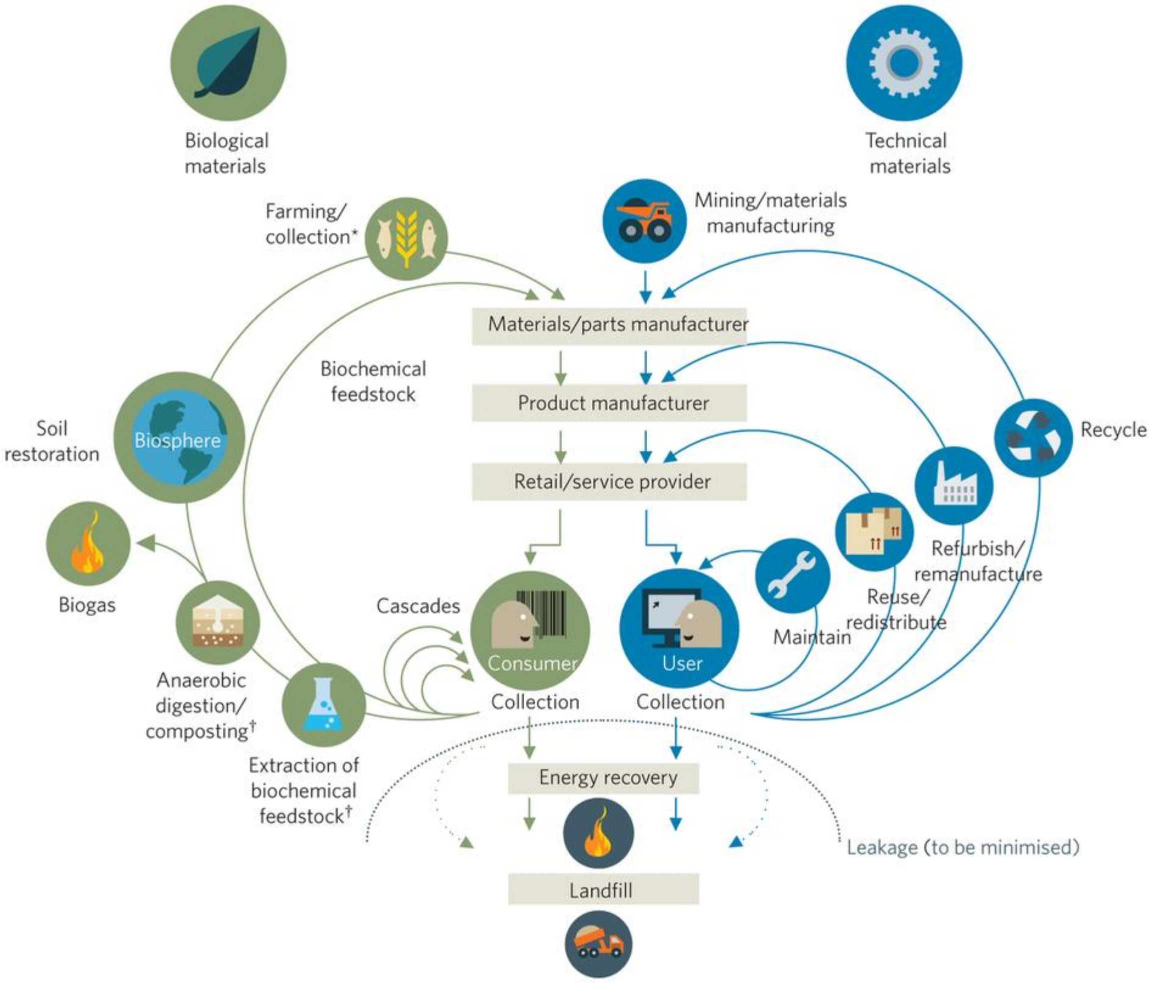


Figure 1. A schematic illustration of the circular economy concept, its components and processes. Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

The ambitions of strengthening circular and bio-based economies are potentially linked to biogas solutions in several ways. The typical way of perceiving the role of biogas solutions is as a final process step in biomass cascading where an energy carrier and bio-fertiliser is produced and the biomass sanitised which we in this report call hygienised. However, the cascading concept still being relevant, biogas solutions can also be viewed as an upcycling process (Martin and Parsapour, 2012) where high value products are generated from waste that different actors perceive as a disposal problem. Development trajectories are difficult to foresee but there is some support that biogas solutions are part of a dynamic innovation culture (Ersson et al., 2015). New initiatives that arise as spin-offs from biogas solutions today include for instance single-cell protein production (Calysta and Unibio as examples of companies[1]) and enzyme harvesting (Inzymes Biotech[2]).

[1] (Calysta Nutrition, 2016; Unibio, n.d.)
[2] (Karlsson and Nygren, 2015)

Aim: This report aims at illustrating the role biogas solutions can play in a future society which is characterised as being more based on circular flows of biomass, and identifying potential benefits of such development. A useful means of addressing that aim is to characterise and analyse direct and indirect effects of existing biogas solutions. This will be performed through an approach consisting of three different parts:

(i) identifying sustainability-related benefits of biogas solutions as they are typically framed by different relevant organisations and agencies in their reports.

(ii) analyse and illustrate how well these benefits are supported by scientific literature.

(iii) illustrating how the identified benefits of biogas solutions relate to the UN sustainable development goals (SDG).

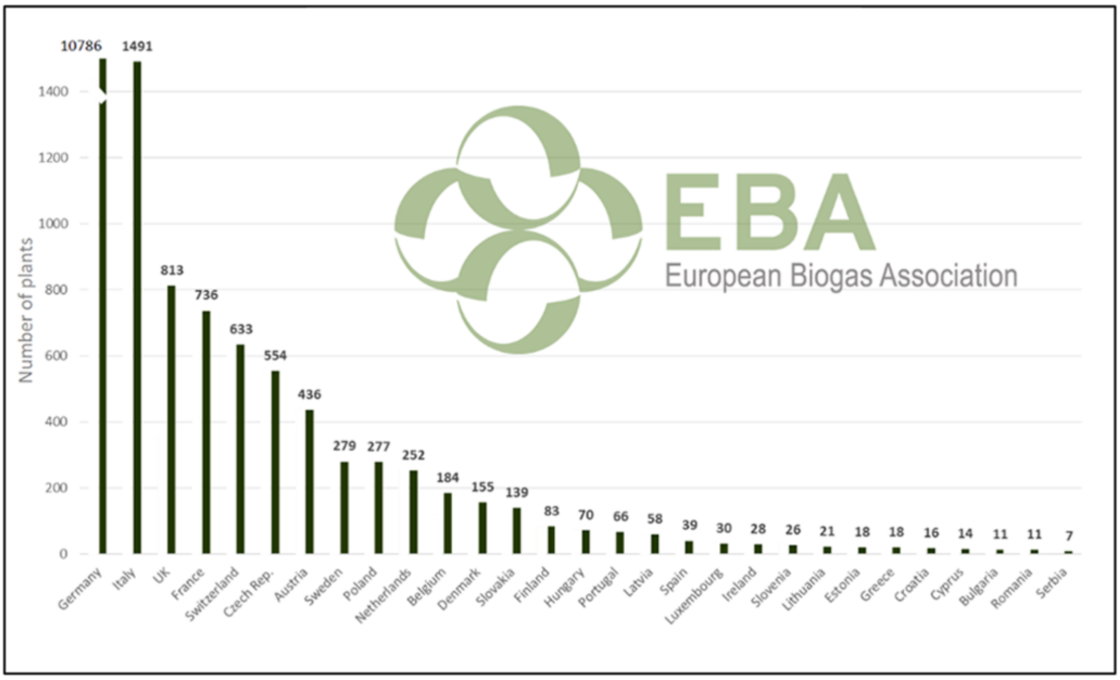
2. Background

2.1 Biogas in History

The formation of biogas has been known since the 1700s where flammable gases from rotting food piles were recognised. But anaerobic digestion has not been around until the 1880s, then as a treatment of waste water. During the 20th century a development of this technique occurred with a focus on stabilising compounds in waste water. As an energy source biogas has historically been more commonly used in developing countries such as China and India. High energy prices lead to decisions in both those countries to try and increase the use of biogas solutions especially in rural areas. The range of biogas solutions increased in the 1970s during the oil crisis as alternative fuels were required. Lately, the use of anaerobic digestion as a treatment of food waste has developed in Europe and even though the production has expanded immensely it is only a few percent of the potential waste that is digested. (Abbasi et al., 2012)

2.2 Biogas in Europe

In Europe the biogas production started off with waste water treatment and is still today a common technique for cleaning waste water as it decreases volumes substantially. It is also more and more common to trap and use landfill gas around Europe. The area which has grown the most recently is the production of biogas and digestate from crops and wastes. In Figure 2 you can see the amount of plants in different countries of Europe. Most of the biogas in Europe is used for heat and electricity production, some is also inserted on the natural gas distribution net after being upgraded (Vagonyte, n.d.). This development has been influenced by *inter alia* national and EU targets and policies.



17 240 biogas plants in Europe (31/12/2014)
Total installed capacity of 8 293 MW_{el}

Figure 2. Source (EBA, 2014).

The EU has the goal to reach 10% biofuels in the vehicle fleet by 2020. The EU especially encourage biofuels from waste materials. A reason for the EU's quest to increase their own energy production is also to decrease the share of imported energy. Already today, the import share of crude oil is more than 90% and natural gas 66% (European Commission, 2016a), much of which comes from Russia and the Middle East. To ensure a secure energy supply in the future, the EU therefore aims to increase domestic energy production.

The European Union has also launched a circular economy package which set new waste management targets to be met by 2030. Waste amounts for reuse and recycling should reach at least 65% and landfill may not exceed 10% of municipal waste. There will also be an extended producer responsibility which should covers costs for the end of life treatments for specific products. Producers are also expected to design their products to facilitate recycling and reuse. The package promotes prevention, the first option in the waste hierarchy, and reuse for all types of products and also food waste. They also propose to stimulate industrial symbiosis – a concept where one industry's by-product is turned into another industry's raw material (Chertow, 2007). However the definitions of waste in EU today can sometimes be too strict and make industrial symbiosis hard to realise. The EU also wants to develop quality standards for secondary raw materials to assure more producers use secondary materials in their production. Bio-fertiliser should get a more important role in the circular economy and bio-fertiliser from food waste, manure or industries should be utilised. (European Commission, 2016b)

The plan present five areas with priority: plastics, food waste, critical raw materials, construction and demolition **and biomass and bio-based products.** There are several measures to consider regarding legislation, communication, implementation, indicators, standards, support and financial aids. But the EU also tries to consider the contribution of circular economy to the bio-economy. (European Commission, 2016b)

2.3 Biogas in Sweden

Sweden is one of the countries in the EU who has increased biogas production the recent decades. Compared to other countries, Sweden has a large share of the biogas upgraded and used as vehicle fuel. Reasons for this could be that electricity is fairly cheap and that the electrical power sector in Sweden does not rely on fossil sources as the transport fuel market does and biogas therefore has a larger impact in the transport sector. In Sweden there are goals regarding food waste saying that by 2018 50% of waste from households, restaurants and stores shall be treated to recirculate nutrients and 40% should be treated so that also energy is being captured (Naturvårdsverket, 2016). There are two common ways to recirculate nutrients, composting or anaerobic digestion, but only the latter also captures energy. Another goal is that Sweden shall have 50% renewable energy in the energy sector by 2020 and within the transport sector at least 10% of the energy used should be renewable (Prop. 2008/09:163). Sweden has also long- term goals where the aim is to have zero greenhouse gas emissions until 2045 (SOU 2016:21). Biogas solutions can therefore contribute to reach those goals.

3. Methodology

The methodology used for this study is pictured in Figure 3 as well as described in this chapter. The first part of the methodology was to find and select benefits of biogas solutions that were described on web pages and in reports by organisations or agencies involved in biogas or energy development. Specifically trade organisations were picked as they were expected to highlight as many benefits with biogas as possible. Also energy agencies were selected in this process. This study summarises and characterises these benefits as they are described by these organisations. It is thus not the authors of this report who decide what is considered a benefit.

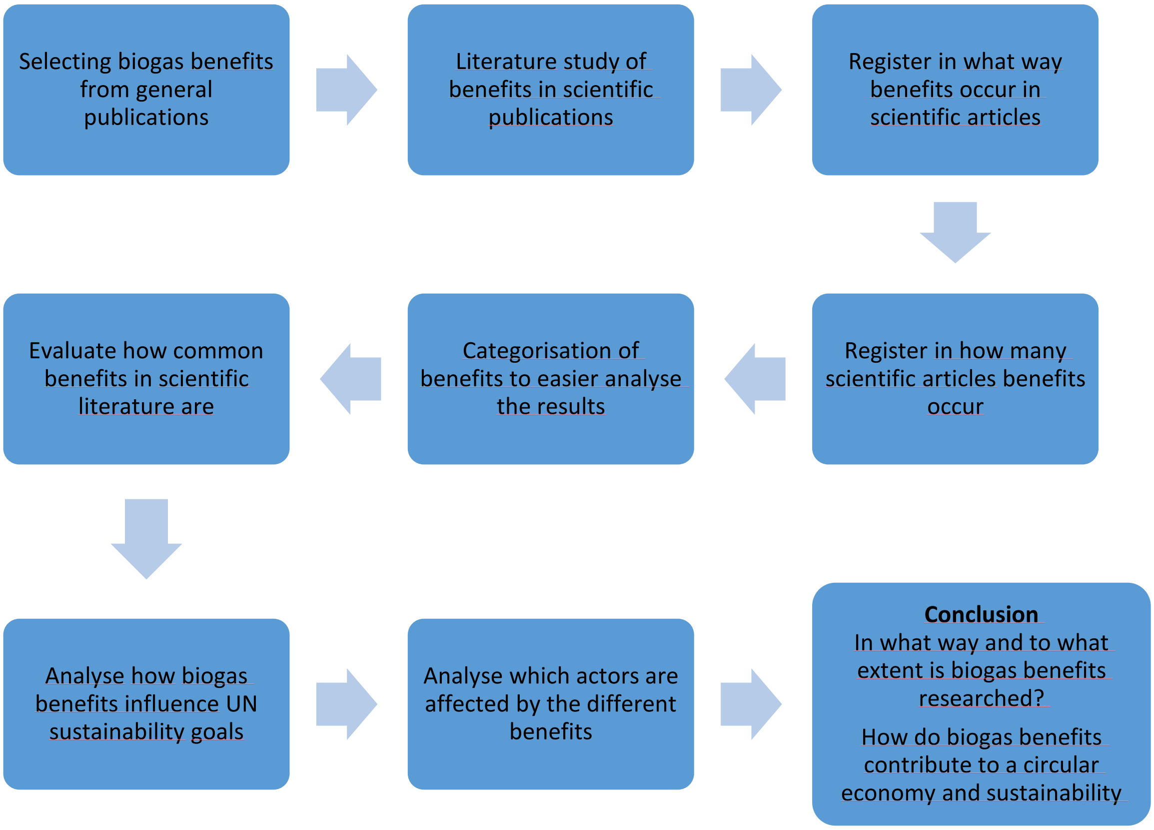


Figure 3. Methodology process.

The chosen reports and materials for extracting benefits include biogas organisations in Sweden, and Europe. Ten reports or web pages were selected and analysed regarding benefits of biogas solutions (Table 1) before saturation of new benefits was reached. The benefits mentioned were then listed and noted in an excel sheet.

Table 1. Sources for picking benefits regarding biogas for further research.

(Biogasportalen.se, 2014a)	Web page regarding societal benefits with biogas solutions. The owners of the site are Energigas Sverige, a trade organisation
(Biogasportalen.se, 2014b)	Web page regarding environmental benefits with biogas solutions. The owners of the site are Energigas Sverige, a trade organisation
(Energigas Sverige et al., 2015)	A new biogas strategy proposal for Sweden written by several actors involved in biogas development
(Energimyndigheten, 2010)	A biogas strategy written by the Swedish energy agency.
(WSP, 2011)	A report by Biogas Öst together with WSP which studies benefits from biogas development in the mid eastern parts of Sweden.
(EBA, 2011)	A folder about biogas solutions in Europe written by the European Biogas Association.
(Svenska Gasföreningen, n.d.)	Information folder regarding biogas solutions written by the Swedish Gas Association.

(Grontmij AB, 2009)	A Swedish report where the focus is to find bottlenecks in today's system and give proposals to increase biogas production.
(Club Biogaz, 2012)	A French brochure describing biogas benefits, written by the Biogas Association of France.
(Energikontoret Norra Småland, 2016)	A GAP-analysis of added values from biogas solutions in the Jönköping region in Sweden

When a list of more than 30 benefits was set, the scientific literature study commenced.

3.1 Scientific literature study

Each benefit found needed its own search which was performed using the search words in appendix 1. As the literature study is quite substantial the words listed for each search is shown. The search words were combined in different ways to assure as many articles as possible were found.

Sometimes the key words were adjusted because very few articles were found. Synonyms were used or the search word "biogas" was replaced by digestate or anaerobic digestion if it was more suitable, see appendix 1. This gives a larger possibility to find articles dealing with a specific benefit in a scientific way but it also provides hints regarding what benefits scientific articles deal with. Through this, it is possible to assess how strongly a certain benefit is supported by scientific publications. This depends on how many articles are found on the topic and if the benefit is the main focus of the article or just mentioned in passing.

The results from the searches offers an indication as to what extent the area concerning each benefit has been researched and also if the results actually imply positive or negative effects. The selected articles need to deal with at least one benefit as study object. Those articles may however mention or reference other benefits. This selection was done to avoid the massive amount of articles which mentions a lot of benefits without actually studying them more deeply. When reading the articles, three different levels of support were identified. Whether the benefit in question was only mentioned, mentioned with a reference or if it was the studied topic of the article. These categories were termed "mentioned", "referenced" and "study object". For each time a benefit fell into these categories it was marked and in the end added together for Figure 6. Almost 60 scientific articles were read and information regarding benefits has been extracted and inserted to an excel document where all benefits were listed.

3.2 Analysis methodology

The benefits were categorised, into the four categories Biogas, Digestate, Treatment and Concept. The categories represent different products or services provided by biogas solutions. The concept category captures more general and indirect benefits.

To show which impact these benefits has on sustainability they were related to the 17 Sustainable Development Goals (SDGs) set by the UN, see Figure 4. These goals include economic, environmental and social aspects of sustainability and by categorising benefits of biogas solutions into the SDGs we can illustrate how multifaceted impact from biogas solutions can be.

The different categories of biogas benefits were inserted accordingly to the 17 SDGs (see tables 5-8). Furthermore, the other studied aspect was to identify which actor that is affected by the different benefits. Actors are divided into suppliers, producers, consumers and society. Suppliers indicate actors delivering substrates to anaerobic digestion, producers are the biogas plant owners or for example waste water treatment plants using anaerobic digestion, consumers includes the customers of biogas as heat, power, fuel, raw gas or bio-fertiliser. The final actor, society, account for benefits which affect the region, its inhabitants and society at large. The benefit- categories are used to reduce the complexity of this analysis as there are many benefits fitting for each sustainability goal. The idea is that the overview will show what product or service biogas solutions contribute with towards the goals. The aim of this task is to show that biogas solutions can contribute to several of the sustainability goals and therefore the same category can be inserted several times if it contributes to more than one goal. The same goes for the actors who also may benefit from the same product on the same goal. In the analysis the benefit categories were first linked to each sustainability goal. For example, to the SDG of "Decent work and economic growth" benefits such as economic growth, employment, self-supply of energy, waste water treatment and higher yields among others were identified. These were then connected to their respective category (Biogas, Digestate, Treatment or Concept) and then arranged on each sustainability goal to each affected actor.

Figure 4. UN sustainability goals (SDG). (UN, 2015)

To validate the analysis two researchers independently inserted the benefit categories in the matrix. They then discussed the different interpretations and compiled a common matrix where the benefit categories were inserted.

A way of structuring the SDGs have been proposed by researchers at Stockholm Resilience Centre where societal and economic activities are seen as embedded in the biosphere. Technologies and policies that contribute to several of the goals at the same time are especially valuable. However, that may also imply that they are more difficult to implement due to their broader embeddedness in many sectors. In the analysis the writers have chosen to structure the comments according to Figure 5.

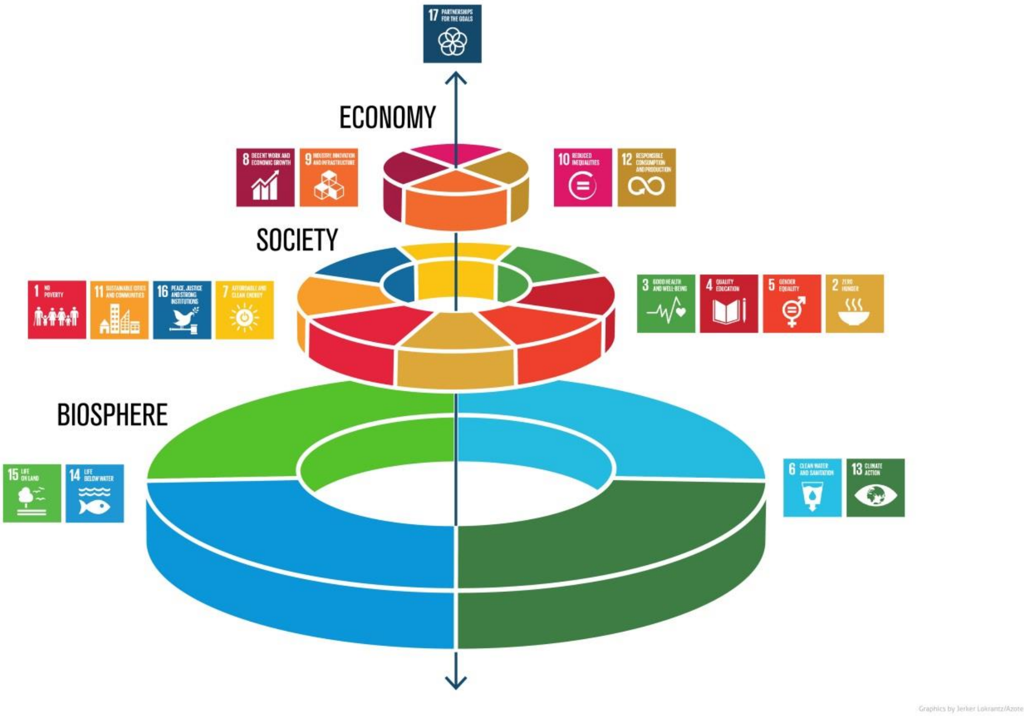


Figure 5. Model for sustainable development goals divided into the three sustainability aspects. Source: (Stockholm Resilience Centre, 2016)

3.3 Scope

We are only choosing aspects listed as benefits by others than the author in this study. The limitations regarding the choice of grey literature depended on languages understood by the author and reports with more general content regarding biogas were chosen as it was assumed these would cover as many benefits of biogas solutions as possible. There is a risk of missing benefits which are specific to parts of the biogas solutions such as digestate, waste treatment or use of bio- methane when doing this. Scopus was used as database when the scientific literature search was made. In the analysis, each sustainability goal has sub-goals which are more specific and measureable, but these were not considered in this analysis.

3.4 Method criticism

Choosing articles which were relevant for the study was a massive job and many hundreds of abstracts has been read to find articles where the authors could define if the benefits proposed was a study object. The author has tried to keep the correlation between amount of hits and amount of articles chosen for the benefits to improve the literature review. Another weakness is that the literature is in English. The review figure will therefore not have used articles in Swedish but in chapter 5.1-5.4 other relevant research has been commented upon. Also research from institutes are mentioned in those chapters as they do a lot of research which do not turn up when using the chosen database. It has not been possible to read everything in a specific field and the author rely on the selection of articles which is trying to show trends and patterns of the research field.

The analysis with the sustainability goals was very challenging. As the work progressed and more articles were read the more goals could be ticked off. Each time the analysis has been reviewed new benefits were identified to fit to a specific actor or a goal. However, it is important to do similar analysis for different alternative technologies in order to be able to better conclude regarding the contributions from biogas solutions.

4. Benefits

4.1. List of benefits

The list in table 2 with benefits is the outcome of the read through done on webpages and reports written by trade organisations or agencies. How often a specific benefit occurs is shown as a number inserted after each benefit in parenthesis to indicate how many out of the 10 sources used who mentioned this specific benefit.

Table 2. List of benefits from webpages and government materials. The number in parenthesis shows how many publications has mentioned a specific benefit.

Reducing CO_2- emission (9)	Sustainable energy supply (4)
Producing fossil free fuel (8)	Less noise (4)
Less particles (8)	Reducing odour (3)
Producing fertiliser (8)	Improving soil structure (3)
Renewable energy (8)	Developing rural areas (3)
Treating organic waste (7)	Balanced crop rotation (3)
Increasing employment (7)	High content of ammonium (2)
Less NOx (6)	Enabling organic farming (2)
Nutrient circulation (6)	Less pesticides used in agriculture (2)
Reducing methane from manure (6)	Hygienising waste (2)
Self-supply of energy for the nation (6)	Moving towards a circular economy (2)
Producing heat and power (6)	Energy efficient to produce (2)
Exporting technology (5)	Increasing resource efficiency (1)
Reducing use of mineral fertiliser (5)	Increasing yield for farmers (1)
Increasing economic growth (4)	Reducing methane from landfills (1)
Increasing research and innovation (4)	Increasing small scale biogas solutions for cooking and power (1)
Less eutrophication (4)	Treating waste water (1)

4.2 Categorisation

The categorisation is made to easier connect different benefits into subthemes. Benefits connected to the products and services which biogas solutions contributes with seems fit as well as a more overall concept category, seen in table 3. This is to assure that there are no overlaps in the categories. Most benefits can be directly connected to the production of biogas or bio-fertiliser alternatively to the treatment of wastes. These categories will then represent the different benefits listed below each category and the analysis will be more comprehensible if categories are used rather than each benefit.

Table 3. Categorisation of biogas benefits

BIOGAS	DIGESTATE	TREATMENT	THE CONCEPT
1. Renewable energy	11. Balanced crop rotation	22. Treating waste water	28. Increasing research and innovation

2. Sustainable energy supply	12. Less pesticides used in agriculture	23. Hygienising waste	29. Moving towards a circular economy
3. Energy efficient to produce	13. Improving soil structure	24. Treating organic waste	30. Exporting technology
4. Producing fossil free fuel	14. Increasing yield for farmers	25. Increasing resource efficiency	31. Increasing employment
5. Producing heat and power	15. High content of ammonium	26. Reducing methane from landfills	32. Increasing economic growth
6. Self-supply of energy for the nation	16. Enabling organic farming	27. Reducing methane from manure	33. Increasing small scale biogas solutions for cooking and power
7. Reducing CO_2-emission	17. Less eutrophication		34. Developing rural areas
8. Less NOx	18. Circulating nutrients		
9. Less Particles	19. Producing fertiliser		
10. Less noise	20. Reducing use of mineral fertiliser		
	21. Reducing odour		

5. Biogas benefits in scientific literature

After having selected more than 30 benefits mentioned in reports or webpages, they were evaluated. Table 4 show which references that has been used and sorted according to in what way they discuss the benefits found in literature. * means that the authors have mentioned the benefits, ** means that it has been mentioned with a reference after and *** means that the authors has the specific benefit as a case study. In table 4 we also have comments if there is something specific in the articles which has been revealed or should be mentioned for better understanding. In figure 6 the results are shown in a diagram where benefits, their number and type of occurrence (mentioned, referenced, study object) in text is shown.

Table 4. Results from scientific literature review of AD related benefits.

Benefits	Sources	Comments
BIOGAS		
1. Renewable energy	(*Alburquerque et al., 2012; Begum and Nazri, 2013; Börjesson, 2008; Börjesson and Mattiasson, 2008; Broun and Sattler, 2016; Chen et al., 2010; Costa et al., 2013; Cuéllar and Webber, 2008; De Meester et al., 2012; Demirbas, 2008; Demirel et al., 2010; Edwards et al., 2015; Fierro et al., 2014; Henke and Theuvsen, 2014; Insam et al., 2015; Kaspersen et al., 2016; Kong et	Biogas is renewable according to the definition from the EU commission: "Renewable energy sources are defined as renewable non fossil energy sources: wind, solar, geothermal, wave, tidal,

	al., 2012; Lošák et al., 2015; Mæng et al., 1999; Nasir et al., 2012; Odlare et al., 2011; Papacz, 2009; Pöschl et al., 2010; Pugesgaard et al., 2014; Sharma et al., 2013; Siegmeier et al., 2015; Thamsiriroj et al., 2011; Vac and Popita, 2015; Vijay et al., 1996) (**Sumathi and Muthu, 2012)	hydropower, biomass, landfill gas, sewage treatment plant gas and biogases."
2. Sustainable energy supply	(*Alburquerque et al., 2012; De Meester et al., 2012; Demirel et al., 2010; Edwards et al., 2015; Lopes et al., 2012; Odlare et al., 2011; Siegmeier et al., 2015; Sumathi and Muthu, 2012; Varel et al., 2012)	This is debatable as it requires the biomass to be produced sustainably to generate sustainable biogas. But several articles mention biogas as sustainable.
3. Energy efficient to produce	(*Odlare et al., 2011) (**Ravi et al., 2015) (***Barta et al., 2013; Begum and Nazri, 2013; Pöschl et al., 2010)	Energy efficiency is calculated as Used energy/Produced energy to see if biogas plants requires more energy than they produce. It seem to depend mainly on what substrates are used in the process.
4. Producing fossil free fuel	(*Appels et al., 2008; Begum and Nazri, 2013; Börjesson and Mattiasson, 2008; Chen, 1997; Cuéllar and Webber, 2008; Demirel et al., 2010; Kong et al., 2012; Sharma et al., 2013) (**Pöschl et al., 2010; Thamsiriroj et al., 2011) (***Börjesson and Berglund, 2006)	One of the uses with biogas is vehicle fuel which is fossil free as biomass is seen as renewable. Some of the studies compare environmental performance when biogas replace fossil fuels.
5. Producing heat and power	(*Appels et al., 2008; Begum and Nazri, 2013; Cuéllar and Webber, 2008; De Meester et al., 2012; Demirel et al., 2010; Kong et al., 2012; Mueller, 2007; Odlare et al., 2011; Rodríguez-Tapia et al., 2010) (**Pöschl et al., 2010) (***Kaspersen et al., 2016)	Heat and power is also a way to use the biogas in a generator. The case studied do several assessments to see whether it is feasible to produce heat and power environmentally or economically.
6. Self-supply of energy for the nation	(*Brown, 2006; Demirel et al., 2010; Fierro et al., 2014; Mæng et al., 1999; Thamsiriroj et al., 2011; Zhu and Hiltunen, 2016) (**Chen, 1997; Henke and Theuvsen, 2014; Vac and Popita, 2015) (***Edwards et al., 2015; Pugesgaard et al., 2014; Rahim and Hosam-E-Haider, 2015; Vijay et al., 1996)	This benefit is not discussed much on the national level but rather local self-supply on a farm or an industry, this of course leads to a larger self-supply for the nation as well.
7. Reducing CO_2- emission	(*Begum and Nazri, 2013; Börjesson and Mattiasson, 2008; Broun and Sattler, 2016; Demirel et al., 2010; Edwards et al., 2015; Garrison and Richard, 2005; Mæng et al., 1999; Pöschl et al., 2010; Ravi et al., 2015; Sharma et al., 2013; Siegmeier et al., 2015) (**Costa et al., 2013; Vac and Popita, 2015) (***Börjesson and Berglund, 2006; Cuéllar and Webber, 2008; Fierro et al., 2014; Gustavsson et al., 1995; Jat et al., 2000; Kaspersen et al., 2016; Mueller, 2007; Pugesgaard et al., 2014; Thamsiriroj et al., 2011)	This is a well-researched area as climate focus has been important the last decades. The CO_2 reduction is mainly due to the replacement of fossil fuels.
8. Less NO_x	(*Fierro et al., 2014; Gustavsson et al., 1995; Thamsiriroj et al., 2011) (***Börjesson and Berglund, 2006; Jat et al., 2000; Mueller, 2007; Ravi et al., 2015).	Articles regarding less emission of NO_x, are often mentioned together with studies on CO_2 emissions as they are system analyses and different emissions are evaluated.

9. Less particles	(*Fierro et al., 2014; Gustavsson et al., 1995; Jat et al., 2000; Sharma et al., 2013; Thamsiriroj et al., 2011). (***Börjesson and Berglund, 2006; Ravi et al., 2015; Semple et al., 2014)	Particle concentrations are evaluated in articles regarding emissions from biogas combustion.
10. Less noise	(**Fierro et al., 2014) (***Ravi et al., 2015; Tang et al., 2006)	A dual fuel vehicle show reduced noise when biogas and diesel is mixed. Another study uses raw gas in an engine which results in higher noises than a diesel engine. More studies are required. It is also likely that manufacturers has performed these tests and drawn conclusions from this, But it has not been found in this literature search.
DIGESTATE		
11. Balanced crop rotation	(*Siegmeier et al., 2015; Vac and Popita, 2015) (***Pugesgaard et al., 2014; Stinner et al., 2008)	The studies focus on organic farming where ley crop rotations are implemented for biogas production. Choice of crop rotation can be important for both yield in biogas plants as well as yields on the fields used.
12. Less pesticides used in agriculture	(*Börjesson and Berglund, 2006; Siegmeier et al., 2015) (**Fierro et al., 2014) (***Chen, 1997; Shang et al., 2011)	Bio-fertiliser has inhibitory effects on some pathogens which can attack crops. Farmers using this fertiliser can therefore use less pesticides.
13. Improving soil structure	(*Chen, 1997; Edwards et al., 2015; Lopes et al., 2012; Nasir et al., 2012; Sharma et al., 2013; Siegmeier et al., 2015; Vac and Popita, 2015) (**Insam et al., 2015; Kouřimská et al., 2012) (***Frøseth et al., 2014; Odlare et al., 2011)	The studies show that the microbiology in the soil is improved and therefore contribute with better respiration and organic carbon to the soil which is beneficial.
14. Increasing yield for farmers	(*Chen, 1997; Möller and Stinner, 2009; Odlare et al., 2011; Sharma et al., 2013; Siegmeier et al., 2015) (**Kouřimská et al., 2012; Möller and Müller, 2012; Pugesgaard et al., 2014; Semple et al., 2014) (***Crolla et al., 2013; Lošák et al., 2015)	This benefit is debatable as different comparisons with bio-fertiliser and mineral fertiliser show different results. It seem to depend on several parameters.
15. High content of ammonium	(*Blumenstein et al., 2016; Börjesson and Berglund, 2006; Crolla et al., 2013; Frøseth et al., 2014; Kouřimská et al., 2012; Siegmeier et al., 2015; Vac and Popita, 2015; Varel et al., 2012; Zhu and Hiltunen, 2016) (**Möller and Müller, 2012) (***Möller and Stinner, 2009)	The ammonium content in digestate seem to depend on the pH and nitrogen concentration.
16. Enabling organic farming	(*Blumenstein et al., 2016) (***Pugesgaard et al., 2014; Siegmeier et al., 2014).	The studies focus on organic farms which are implementing biogas solutions rather than the opposite. Reducing fossil dependence and getting certified nutrient are important for organic farmers.

17. Less eutrophication	(*Frøseth et al., 2014; Thamsiriroj et al., 2011; Vac and Popita, 2015) (**Börjesson and Berglund, 2006; Chen, 1997; Fierro et al., 2014) (***Crolla et al., 2013; Kaspersen et al., 2016; Siegmeier et al., 2014)	This is a debatable topic as there are always risk of nitrogen leakage when applying fertilisers to soil. It seem to depend on aspects such as time, weather and application rates. A twist on this topic is one article discussing reduced eutrophication of the sea as algae from the sea is used in biogas plants. NOx emissions from exhaust gases are also lower from biogas combustion and it also reduce eutrophication.
18. Circulating nutrients	(*Börjesson and Berglund, 2006; Börjesson and Mattiasson, 2008; Edwards et al., 2015; Fierro et al., 2014; Odlare et al., 2011; Zhu and Hiltunen, 2016). (***Chen, 1997; Kaspersen et al., 2016)	This is mentioned in several articles as something positive. The studies are discussing cases where the nutrient circulation itself gives benefits.
19. Producing fertiliser	(*Börjesson and Berglund, 2006; Brown, 2006; Chen, 1997; Chen et al., 2010; Costa et al., 2013; De Meester et al., 2012; Demirel et al., 2010; Kaspersen et al., 2016; Kong et al., 2012; Kouřimská et al., 2012; Mueller, 2007; Nasir et al., 2012; Odlare et al., 2011; Rodríguez-Tapia et al., 2010; Siegmeier et al., 2014; Sumathi and Muthu, 2012; Thamsiriroj et al., 2011; Vac and Popita, 2015; Varel et al., 2012) (**Cuéllar and Webber, 2008; Edwards et al., 2015; Zhu and Hiltunen, 2016) (***Alburquerque et al., 2012; Blumenstein et al., 2016; Insam et al., 2015; Lopes et al., 2012; Lošák et al., 2015; Möller and Müller, 2012; Möller and Stinner, 2009)	Digestate can be used as fertiliser and will often replace fossil fertilisers. Having such a product is of course a benefit for the biogas production but the bio-fertiliser in itself also generate several benefits.
20. Reducing use of mineral fertiliser	(*Börjesson and Mattiasson, 2008; Demirel et al., 2010; Fierro et al., 2014; Lopes et al., 2012; Möller and Müller, 2012; Sharma et al., 2013; Thamsiriroj et al., 2011) (**Pöschl et al., 2010) (***Kaspersen et al., 2016; Kouřimská et al., 2012; Lošák et al., 2015).	As bio-fertiliser replace mineral fertiliser at least in conventional farming less environmental impact from mineral fertiliser can be accounted.
21. Reducing odour	(*Jat et al., 2000; Mueller, 2007; Thamsiriroj et al., 2011) (**Costa et al., 2013; Cuéllar and Webber, 2008; Fierro et al., 2014; Kaspersen et al., 2016)(***Crolla et al., 2013; Varel et al., 2012).	Compared to manure before digestion bio-fertiliser has a tendency to smell less. It seem to depend on the substrates.
TREATMENT		
22. Treating waste water	(*Kong et al., 2012; Thamsiriroj et al., 2011) (**Costa et al., 2013; Edwards et al., 2015) (***Appels et al., 2008; Haberl et al., 1991)	Several articles scanned through came from the 80s and 90s. Municipal waste water treatment benefits with anaerobic digestion as the amount of sludge is reduced and hygienised.

23. Hygienising waste	(*Alburquerque et al., 2012; Brown, 2006; Chen et al., 2010; Edwards et al., 2015; Insam et al., 2015; Siegmeier et al., 2015; Thamsiriroj et al., 2011; Vac and Popita, 2015) (**Appels et al., 2008; Chen, 1997; Costa et al., 2013; Fierro et al., 2014; Pant, 2011) (***Oikonomou et al., 2014; Varel et al., 2012).	The hygienisation which occur in anaerobic digestion chambers seem to kill some pathogens due to the temperature in the chambers. Sometimes a specific hygienisation step is required.
24. Treating organic waste	(*Appels et al., 2008; Börjesson and Mattiasson, 2008; Cuéllar and Webber, 2008; Fierro et al., 2014; Haberl et al., 1991; Jat et al., 2000; Odlare et al., 2011; Thamsiriroj et al., 2011) (**De Meester et al., 2012; Demirel et al., 2010; Kaspersen et al., 2016; Pöschl et al., 2010) (***Costa et al., 2013; Edwards et al., 2015; Kong et al., 2012; Lopes et al., 2012; Nasir et al., 2012; Rodríguez-Tapia et al., 2010; Schmidell et al., 1986; Sumathi and Muthu, 2012; Zhu and Hiltunen, 2016)	Anaerobic digestion as a waste treatment became popular in the 80s and some research is found back then regarding the actual treatment itself. Today's literature focus more on how the waste treatment can be used or policy directions.
25. Increasing resource efficiency	(*Börjesson and Berglund, 2006; Chen, 1997; Vijay et al., 1996) (***Börjesson and Mattiasson, 2008; De Meester et al., 2012).	Biogas solutions can be resource efficient especially if the biogas production comes from waste products or is integrated in a certain flow.
26. Reducing methane from landfills	(*Demirbas, 2008; Demirel et al., 2010; Fierro et al., 2014; Lopes et al., 2012; Nasir et al., 2012) (*Edwards et al., 2015) (***Broun and Sattler, 2016; Kong et al., 2012)	As organic material is diverted from landfills slippages will decrease. Methane from landfills is a common problem if there is organic waste.
27. Reducing methane from manure	(*Nasir et al., 2012; Siegmeier et al., 2015) (**Börjesson and Berglund, 2006; Börjesson and Mattiasson, 2008; Kaspersen et al., 2016; Pugesgaard et al., 2014) (***Cuéllar and Webber, 2008; Fierro et al., 2014; Garrison and Richard, 2005)	Methane slippage from manure storages is common. Instead of just keeping the manure farmers can digest it and use the methane as biogas instead.
THE CONCEPT		
28. Increasing research and innovation	(*Börjesson and Mattiasson, 2008; Edwards et al., 2015; Mæng et al., 1999; Nasir et al., 2012; Zhu and Hiltunen, 2016)	All new technologies require continuous research and innovation. This benefit therefore do not seem researched specifically.
29. Moving towards a circular economy		Circular economy is mentioned in some Chinese reports about biogas but it is not really discussed and the connections has not been researched. Perhaps it is because it lie in the definition of circular economy to have biogas solutions.
30. Exporting technology	(***Mæng et al., 1999)	As biogas technology is needed all around the world there is also an opportunity to export if technology is well developed.

31. Increasing employment	(*Demirbas, 2008; Demirel et al., 2010; Edwards et al., 2015; Pant, 2011; Rodríguez-Tapia et al., 2010; Thamsiriroj et al., 2011; Vac and Popita, 2015) (**Fierro et al., 2014) (***Henke and Theuvsen, 2014; Mæng et al., 1999; Mueller, 2007; Vijay et al., 1996).	Employment calculations differ in different cases. The directly connected employment possibilities are at the biogas plant, transports of substrates and bio-fertiliser as well as some marketing etc. Indirect employment could be researchers, farmers and industry delivering to the biogas plant. Some articles also count the losses of employment in sectors being replaced by the biogas plant, giving a lower total number. Mainly local employment is discussed.
32. Increasing economic growth	(*Edwards et al., 2015; Mæng et al., 1999). (**Henke and Theuvsen, 2014) (***Demirbas, 2008; Rahim and Hosam-E-Haider, 2015)	Economic growth from biogas production is not directly researched but some articles claim that economic growth and energy growth is connected and thus the more energy that is generated the more economic growth.
33. Increasing small scale biogas solutions for cooking and power	(*Demirel et al., 2010; Rahim and Hosam-E-Haider, 2015; Rodríguez-Tapia et al., 2010) (***Brown, 2006; Chen, 1997; Demirbas, 2008; Pant, 2011; Semple et al., 2014; Sharma et al., 2013; Sumathi and Muthu, 2012; Vac and Popita, 2015; Vijay et al., 1996)	Articles regarding this benefit often study cases in developing countries. Spin off benefits are identified such as better health and more time to spend for women and children who are often responsible for the cooking at home usually with wood or dung.
34. Developing rural areas	(*Demirel et al., 2010; Pant, 2011; Rodríguez-Tapia et al., 2010; Siegmeier et al., 2015; Sumathi and Muthu, 2012; Vac and Popita, 2015) (**Edwards et al., 2015; Kaspersen et al., 2016) (***Chen et al., 2010; Pugesgaard et al., 2014).	The circular system biogas solutions can offer can be developing for a country side. What is farmed can also be digested and used again on fields. It also gives local jobs and local infrastructure.

5.1 Biogas

The biogas section consists of ten different benefits. In figure 6 we see that the most studied case is the CO_2-reduction. But also *energy efficiency, self-supply of energy* and *less NOx* are covered in case studies. CO_2-reduction is common as the reduction can be accounted for both the replacement of fossil fuels but also the replacement of mineral fertiliser which requires large amount of often fossil energy to be produced. As mentioned, in the commentary field of table 4, the self-supply is connected to regional or local areas but it means at the same time that imported energy can be reduced. The least frequent benefits when looking at the total in the bars are *energy efficiency* and *noise reduction*. Regarding energy efficiency a Swedish analysis has been done by Berglund and Börjesson (2003). Their conclusions are that energy efficiency depends largely on energy used to produce the feedstock as well as energy use during the process.

Gas engines create the same noises and research regarding natural gas engines could therefore apply to biogas engines as well. But also for natural gas it was hard to find research on noise reduction. What was found was an article where dual-fuel vehicles are tested but they present an argument for the reduced noise: “This reduction in combustion noise may be explained by the improved mixing between air and gaseous fuel which enables the combustion to start smoothly and produces lower pressure rise rate.” (Elnajjar et al., 2011).

5.2 Digestate

Benefits connected to the digestate count to eleven. The most researched benefit is the use of the *digestate as a fertiliser*. It is what is mentioned and studied the most. When using the digestate as a fertiliser several other benefits follow. Among these, *less eutrophication* and *reduced use of mineral fertiliser* are the most studied although several of the articles found in these areas are contradictory. This fact may have led to a large body of research in this area. There seems to be a lack of research regarding the benefits for *ammonium content* in digestate and *odour reduction* but it is also worth mentioning that *crop rotation, pesticides in agriculture and organic farming enabling* should be better researched as well in scientific literature.

Swedish Board of Agriculture has written about the possibilities for organic farming when biogas solutions are implemented (Jordbruksverket, 2005). Also the connection between nutrient cycling and organic farming has been studied in a Swedish book (Salomon and Wivstad, 2013) these aspects are also important for self-dependence of food supply in every country and reduce import of mineral fertiliser. During this extra search a report for the organisation F3 was found to strengthen soil improvement, they present a new benefit for the sustainability of bio-fertiliser. Bio-fertiliser can increase the humus content in the soil which leads to more carbon being bound to the soil. This then become a carbon sink (Björnsson et al., 2013).

5.3 Treatment

The treatments biogas solutions can contribute with has six identified benefits. Among these *treating organic waste* and *hygienisation* are the most occurring ones in the scientific literature and waste treatment is also the most studied. There are also some studies on *methane slips from landfills and manure* but *resource efficiency* and *waste water treatment* do not seem well studied according to figure 6.

In this category an interesting report from IVL, the Swedish environmental research institute regarding anaerobic water treatment is found (Malmaeus et al., 2012). The cases take place in paper mills and the results show that one mill get reduced energy use with the new anaerobic treatment and another reduced chemical need which means both reduce their environmental impact through the anaerobic solution.

5.4 Concept

The concept category, where the benefits due to the implementation of biogas solutions are categorised, there are seven identified benefits. Here we see generally fewer articles except for *small-scale biogas solutions for cooking and power* which is well studied in developing countries. There has also been some studies on *employment* possibilities. More research is probably needed to support conclusions regarding the connection *to circular economy*, *export possibilities* and *the impact on economic growth.*

These are all aspects discussed in biogas Östs report written by the consultancy firm WSP (WSP, 2011) and also the new report from Energikontor Norra Småland discusses these aspects (Anderson, 2016). Regarding export it is hard to find any published research but the Energy agency in Germany has written about technology export in a blog post. Where Craig Morris, the lead author of German Energy Transition discusses this topic and see huge possibilities for technology export (Morris, 2014).

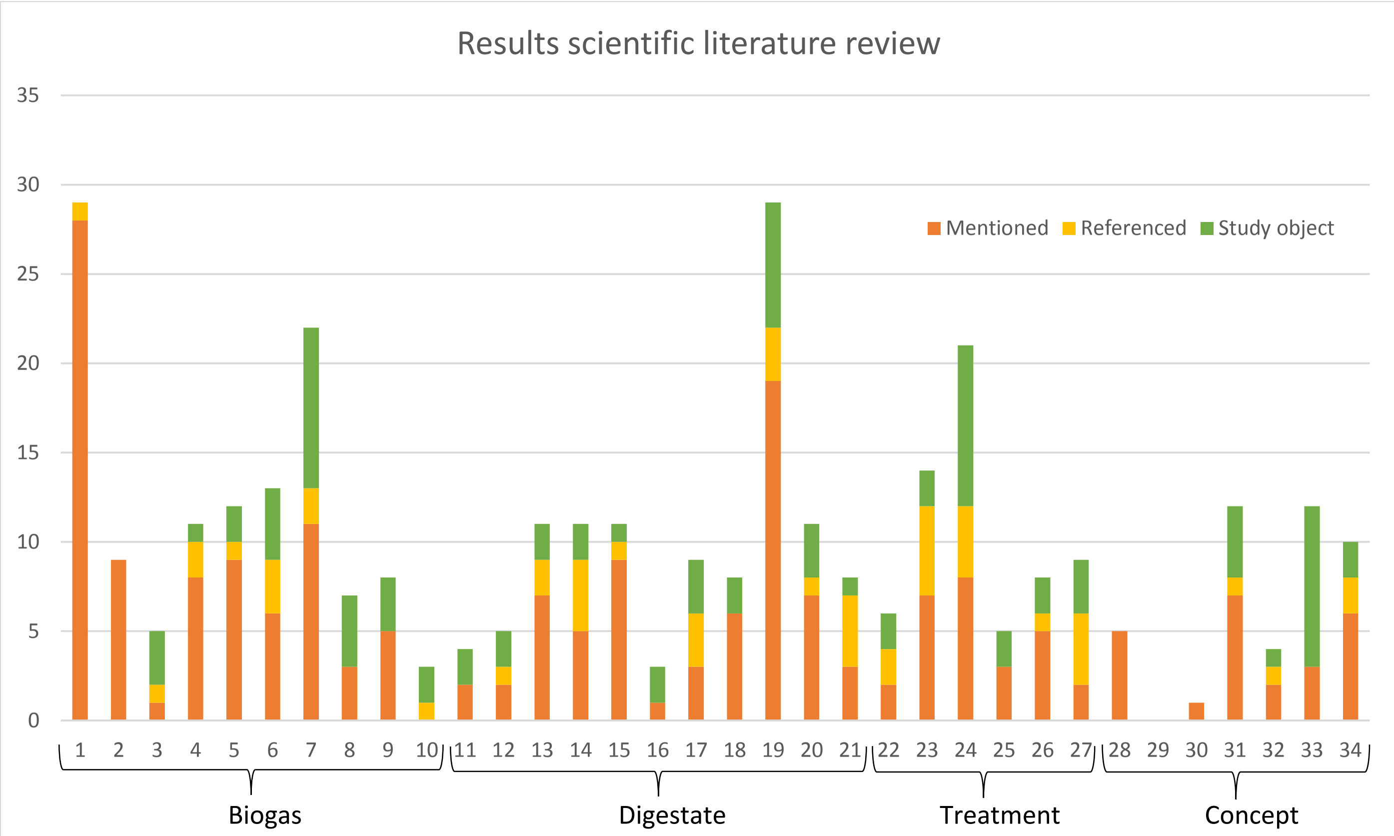


Figure 6. Number of scientific articles (y-axis) in the review, their focus and the levels of support for conclusions regarding the benefits.

1. Renewable energy
2. Sustainable energy supply
3. Energy efficient to produce
4. Producing fossil free fuel
5. Producing heat and power
6. Self-supply of energy for the nation
7. Reducing CO_2- emission
8. Less NOx
9. Less particles
10. Less noise
11. Balanced crop rotation
12. Less pesticides used in agriculture
13. Improving soil structure
14. Increasing yield for farmers
15. High content of ammonium
16. Enabling organic farming
17. Less eutrophication
18. Circulating nutrients
19. Producing fertiliser
20. Reducing use of mineral fertiliser
21. Reducing odour
22. Treating waste water
23. Hygienising waste
24. Treating organic waste
25. Increasing resource efficiency
26. Reducing methane from landfills
27. Reducing methane from manure
28. Increasing research and innovation
29. Moving towards a circular economy
30. Exporting technology
31. Increasing employment
32. Increasing economic growth
33. Increasing small scale biogas solutions for cooking and power
34. Developing rural areas

6. Analysis

There are seventeen sustainability goals setup by the United Nations. These cover all three aspects of sustainability; environmental, social and economic. Each goal has in this study been divided into four sections representing different actors' perspectives. The categories written in the tables correspond to related benefits to show the variety of benefits from different products or services that biogas solutions provide. The method is described in more detail in chapter 3.2.

The flags in the table identify what benefits are relevant in a Swedish context, if the flag is put at the SDG icon it means that all benefits found are relevant in a Swedish context. The results of this analysis is separated into sectors of biosphere, society and economy.

In the biosphere SDGs in table 5, benefits such as fossil free energy, reduced eutrophication, hygienisation, and resource efficiency were important contributions to the sustainability goals. When substrate owners choose to send their biomass to biogas production rather than other waste treatments they might reduce methane emissions from landfills or manure and they minimise eutrophication risk. Most benefits are related to the products biogas and bio-fertiliser as well as the treatment of waste products contributes towards Clean water and sanitation, Climate action, Life under water and Life on land.

Table 5. How biogas benefits relate to the fulfilment of the sustainable development goals for the biosphere and related actors. The categories mentioned indicate in which part of the biogas solution the contribution is made.

	Suppliers	Producers	Consumers	Society
6 CLEAN WATER AND SANITATION	• Treatment	• Treatment	• Digestate • Treatment • Concept	• Biogas • Digestate • Treatment • Concept
13 CLIMATE ACTION	• Treatment	• Biogas • Treatment	• Biogas • Digestate	• Biogas • Treatment
14 LIFE BELOW WATER	• Treatment	• Treatment	• Digestate	• Digestate • Treatment
15 LIFE ON LAND	• Digestate	• Treatment	• Biogas • Digestate	• Biogas • Digestate • Treatment

On the Society level, in table 6, many of the goals relate to developing countries, health, education or industries. The goals are more diverse on this level and it is therefore hard to draw any overall conclusions. Goals; No poverty, Zero hunger, Good health and well-being, Quality education and Gender equality are related to the benefit from biogas solutions common in developing countries and can lead to reduced poverty and hunger due to usage in cooking or electricity production. By having biogas solutions in homes in developing countries, there is support for improved health among women and children since it improves quality of life for women typically responsible for cooking and finding fire-wood. No poverty is affected through employment possibilities, higher yields for farmers or cheaper energy to families. The No hunger-goal will also be influenced through the use of the bio-fertiliser which increases yields and soil conditions. The biogas solutions also lead to the Good health and Well-being goal as biogas burns without as much particles and NO_x as wood. The hygienisation which occur in anaerobic digestion also contributes to better health. There are risks of pollution if bio-waste is not handled correctly. It can also be seen that women and children who can use less time for cooking and collecting fire-wood will have more time available for work or education. However difficult to make any conclusions regarding the indirect effects of such a development, biogas solutions could enable Quality education and Gender equality.

In a Swedish perspective we see a link to the third goal, Good health and well-being, as air pollution status in cities is improved if biogas fuel substitutes fossil fuels in the transport sector. There are also possible links to the Quality education goal on the society level where research and innovation can be applied also in Sweden, and high quality research influence education. The Affordable and clean energy goal, is contributed to by biogas production replacing fossil sources and thus generating lower fossil CO_2-emissions. The Sustainable cities and communities goal are influenced by several biogas benefits. The waste and waste water management is beneficial for all actors in the biogas value chain. Circulating nutrients is also a step towards sustainable cities and communities and using biogas as a sustainable fuel or power source also contributes. The consumers can contribute to sustainable communities when buying digestate or biogas which is a means towards circular economy. The last goal on the society level, Peace, justice and strong institutions is contributed to by aspects such as self-supply of energy, export possibilities and developing rural areas. Many conflicts today can be related to resource disputes and biogas can contribute to the solutions of food and energy supply challenges. The overall reduction of mineral fertiliser could also account to this goal as at least phosphorous is becoming rare and fossil fuel heavy to produce and conflicts may arise.

Table 6. How biogas benefits relate to the fulfilment of the sustainable development goals for the society and related actors. The categories mentioned indicate in which part of the biogas solution the contribution is made.

	Suppliers	Producers	Consumers	Society
1 NO POVERTY	• Biogas • Digestate • Concept	• Biogas • Digestate • Concept	• Biogas • Digestate • Concept	• Biogas • Digestate • Concept
2 ZERO HUNGER	• Digestate • Concept	• Concept	• Biogas • Digestate • Concept	• Biogas • Digestate • Concept
3 GOOD HEALTH AND WELL-BEING	• Treatment	• Treatment	• Biogas 🇸🇪 • Treatment • Concept	• Biogas 🇸🇪 • Digestate • Treatment 🇸🇪 • Concept
4 QUALITY EDUCATION		• Concept	• Biogas • Concept	• Concept 🇸🇪

5 GENDER EQUALITY		• Concept	• Biogas • Concept	• Biogas • Concept
7 AFFORDABLE AND CLEAN ENERGY		• Biogas	• Biogas	• Biogas • Concept
11 SUSTAINABLE CITIES AND COMMUNITIES	• Digestate • Treatment • Concept	• Biogas • Treatment • Concept	• Biogas • Digestate • Treatment • Concept	• Biogas • Digestate • Treatment • Concept
16 PEACE, JUSTICE AND STRONG INSTITUTIONS		• Concept	• Biogas • Concept	• Biogas • Digestate • Concept

On the economic level four goals are included shown in table 7. These are: Decent work and economic growth; Industry, innovation and infrastructure; Reduced inequalities and Responsible consumption and production. Benefits such as employment, economic growth, export and rural development contributes to those. But also there is a role of biogas solutions strengthening industry in several other sectors including the development of bio-refineries. Treatment of waste and waste water, self-supply of energy as well as diversification of the product portfolio are important means here. The digestate consumers can achieve higher yields and thus more income. The consumers play an important role for these goals as they contribute to these goals by purchasing the products.

Table 7. How biogas benefits relate to the fulfilment of the sustainable development goals for the economy and related actors. The categories mentioned indicate in which part of the biogas solution the contribution is made

	Suppliers	Producers	Consumers	Society
8 DECENT WORK AND ECONOMIC GROWTH	• Treatment • Concept	• Biogas • Concept	• Biogas • Digestate • Concept	• Biogas • Digestate • Concept
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	• Biogas • Treatment • Concept	• Biogas • Treatment • Concept	• Biogas • Treatment • Concept	• Biogas • Treatment • Concept
10 REDUCED INEQUALITIES	• Digestate • Concept	• Concept	• Biogas • Concept	• Biogas • Digestate • Concept

12 RESPONSIBLE CONSUMPTION AND PRODUCTION	• Treatment	• Biogas • Treatment • Concept	• Biogas • Digestate	• Biogas • Digestate • Treatment • Concept

For the 17th goal, Partnership for the goals in table 8, biogas solutions can contribute by knowledge and technology exchange between countries. Biogas solutions are also a part of the path towards sustainability and as most countries in the world has agreed upon environmental improvements biogas solutions is one way to together work towards these goals. Many of the environmental problems are global such as clean water and CO_2-emissions and these can be influenced by biogas solutions.

Table 8. How biogas benefits relate to the fulfilment of the sustainable development goals for the partnership and related actors. The categories mentioned indicate in which part of the biogas solution the contribution is made.

	Suppliers	Producers	Consumers	Society
17 PARTNERSHIPS FOR THE GOALS		• Concept	• Biogas • Treatment	• Biogas • Treatment • Concept

The analysis show that biogas solutions potentially can contribute to all seventeen sustainability goals that the UN has set. Some of them in an undisputable and direct way, while others in a more indirect way that can be questioned. More and deeper studies are needed to better capture the sustainability implications of biogas solutions including those of different reference systems. Not all connections are explicitly mentioned in this report as the most important finding is that biogas solutions represent a versatile technology that can contribute to sustainability

7. Concluding discussion

This report compiles benefits of biogas solutions suggested by trade organisations and agencies. More than 30 benefits were found. Many of them show substantial scientific support for the benefits with biogas solutions but also several gaps are revealed. Typically, nutrient circulation, circular economy, resource efficiency, organic farming are less well studied benefits. The reason for them being less studied may be their complexity and the “lack of ownership” among actors

The analysis show that biogas solutions can contribute to all of the 17 UN Sustainable Development Goals. This indicates that biogas solutions need to be studied and understood in a broad, cross-sectoral system perspective. It also shows that it is hard to replace biogas solutions with another technology. It will most likely require several other technologies to get all the benefits as we get today from biogas solutions. As biogas solutions contribute with waste treatment, energy supply and nutrients in one process it is hard for technologies like aerobic waste water treatments, incineration or composting to compete, they only contribute with one aspect each. It can therefore be hard and more costly to reach a sustainable society without biogas solutions. Further studies of how alternative technologies contribute to the SDGs are needed to better understand the effects that biogas solutions have on sustainable development.

If decisions were based on treatment’s contribution to sustainability, biogas solutions would have an advantage according to this study. There has for the last decade been a strong focus on the climate aspect in policy and science instead of looking more broadly at sustainability. Biogas solutions are very strong in climate mitigation but would still benefit from a wider system perspective on assessments in science and policy contexts. Biogas solutions also play a key role in the transition towards both the circular and the bio-based economy. Biogas solutions increase value of its substrate and replaces fossil fuels. It fits well into the biological cycles defined for the circular economy and the energy generated for fuelling a part of the bio-based economy. Both these concepts also involve more high value products in development of biorefineries. As it is important for biorefineries to have an energy recovery step (Wagemann, 2012) and also waste water treatments in their plants then biogas solutions is an alternative to achieve both things at the same time.

Biogas solutions can be seen as the step that closes the loop in societies characterised by circular and bio-based economy where as much high-value products as possible are extracted from the biomass. Biogas solutions are then used for upgrading what is left to useful renewable energy and nutrients that can be used for producing new biomass feedstock. Many new products will need to be produced from biomaterials rather than fossil sources such as bioplastic instead of oil-based plastics. Biogas solutions represent technologies for closing loops in the circular and bio-based economy. If the bio-based economy is to expand there will also be a larger need for biogas solutions and it will be crucial to close nutrient loops and take care of this organic waste for a future sustainable development.

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Appendix 1

Search words used in the literature search for each benefit.

BENEFIT	SEARCH WORDS
Renewable energy	Biogas, renewable,
Treating organic waste	Biogas, anaerobic digestion,
Nutrient circulation	Biogas, digestate, fertilizer, anaerobic, nutrients, recirculation, circulation.
Reduced CO_2- emission	Biogas, greenhouse gases, carbon dioxide, emission,
Less NOx	Biogas, NOx, emission, combustion
Less particles	Biogas, particles, emission, combustion
Less noise	Biogas, fuel, noise, sound,
Sustainable energy supply	Biogas, energy, sustainab*,
Self-supply of energy for the nation	Biogas, energy, self-supply,
Exporting technology	Biogas, technology, export,
Increasing employment	Biogas, anaerobic digestion, employment, jobs, work,
Increasing economic growth	Biogas, anaerobic digestion, economic growth, growth,
Increasing research and innovation	Biogas, research, innovation, technology, development
Reduced methane from landfills	Biogas, methane, landfills, leakage
Reduced methane from manure	Biogas, methane, manure, leakage
Reduced use of mineral fertiliser	Digestate, fertiliser, fertilizer, mineral,
Producing fertiliser	Digestate, anaerobic digestion, fertiliser
Reducing odour	Anaerobic digestion, smell, odour, odor, digestate, bio fertiliser.
Hygienise waste	Anaerobic digestion, waste management, hygieni*, sanit*
Increasing resource efficiency	Biogas, anaerobic digestion, resource efficien*,
Producing fossil free Fuel	Biogas, fossil free, fuel
Producing heat and power	Biogas, heat, power, energy
Energy efficient to produce	Biogas, efficien*, production, energy
Developing countryside	Biogas, anaerobic digestion, countryside, rural,
Balanced crop rotation	Biogas, digestate, bio-fertiliser, crop rotation,
Less pesticides used in agriculture	Biogas, digestate, anaerobic digestion, pesticides,
Improving soil structure	Digestate, fertilis/zer, soil, improvement, soil structure,
Increasing yield for farmers	Digestate, fertilis/zer, yield, crop,
High content of ammonium	Digestate, fertilis/zer, ammonium, nutrients, content
Enabling organic farming	Biogas, anaerobic digestion, organic farming,
Less eutrophication	Biogas, anaerobic digestion, digestate, fertilizer, eutrophication
Moving towards a circular economy	Biogas, circular economy
Increased small scale biogas for cooking and power	Biogas, anaerobic digestion, rural, small scale biogas, equality,
Treating waste water	Anaerobic digestion, treatment, waste water, sludge